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*Translations of Soviet-Bloc Scientific and Technical Literature*



# ON THE INFLUENCE OF FOG ON THE RANGE OF GROUND COMMUNICATION AT THE OPTICAL CARRIER

*Translation*



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## FOREWORD

This translation has been prepared in response to ATD Work Assignment No. 79, Task 43. The article was orginally published as follows:

> Yerkovich, S. P., Yu. V. Pisarevskiy, F. S. Ageshin, and G. A. Tregubov. O vliyanii tumana na dal'nost' nazemnoy svyazi na opticheskoy nesushchey. Elektrosvyaz', no. 12, 1964, 16 - 21.

ON THE INFLUENCE OF FOG ON THE RANGE OF GROUND
COMMUNICATION AT THE OPTICAL CARRIER

*On the basis of an analysis of the various factors affecting the range of communications in the open atmosphere, it is shown that communication at the optical carrier is practicable under fog conditions.*

Little more than three years have elapsed since the first announcement of the development of the quantum generator (laser), but progress in this sphere has reached such a level that there are genuine prospects of utilizing the optical frequency range in all devices — particularly communications systems — that presently operate only in the radio frequency range.

The problem of the practicability of optical-carrier communications in the open atmosphere has acquired great significance. Although the cost of light-guide tubes is not a decisive factor in the planning of communication lines, thanks to the vast carrying capacity of the optical channel, the problem of communications in the open atmosphere remains because of the specifics inherent in communications between moving objects. This article is concerned with the methods of computing the communication range in the open atmosphere in the presence of fog.

In order to simplify our considerations, we will first discuss communications in free space, and then we will take into account the effects of absorption and scattering in the atmosphere. In the absence of atmosphere, the useful signal at the receiver input is determined by the expression:

$$S = \frac{PA}{\Omega R^2},$$

where P is the power of the receiver, A is the area of the receiving antenna, $\Omega$ is the solid angle of the transmitting beam, and R is the distance between the receiver and the transmitter.

In accordance with the Planck formula, if radiation scattered by the atmosphere penetrates into the receiver, the maximum of radiation noise caused by scattered solar radiation lies in the region of 0.5 μ (see Fig. 1). When ground objects which scatter solar radiation are in the line of sight of the receiver, the maximum of radiation noise is somewhat displaced toward longer wavelengths, because Rayleigh scattering in the atmosphere brings about a transformation of the solar-spectrum curve.

The maximum of the radiation noise connected with caloric radiation lies in the region of 10 μ (see Fig. 1). Under ground-

communication conditions, radiation noise due to scattered stellar radiation is slight if one excludes the direct incidence of stellar rays on the receiver.

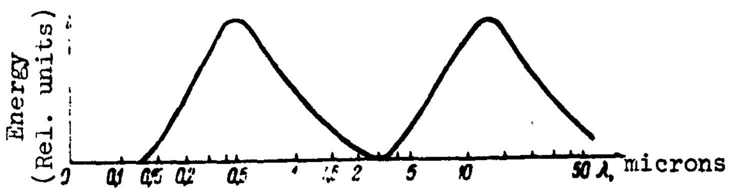


Fig. 1

Receiver noise depends on the structure of the receiver input. If the input element of the receiver is a laser, its internal white noise relative to the input can be determined by the following expression [1]:

$$N = \alpha h f \Delta f, \tag{2}$$

where $\alpha = n_2/(n_2 - n_1)$, $n_1$ and $n_2$ are the populations of the upper and lower layers of the transition, $\Delta f$ is the receiver bandwidth, and f is the frequency of the carrier.

Therefore, the signal-to-noise ratio at the receiver input acquires the form:

$$\frac{S}{N} = \frac{S}{N_{ex} + \alpha h f \Delta f}, \tag{3}$$

where S is determined from (1). In relationship (3) $N_{ex}$ is the power of external noise incident on the receiver band.

In the case of a heterodyne receiver, the signal-to-noise ratio is

$$\frac{S}{N} = \frac{S}{N_{ex} + \beta h f \Delta f}, \tag{4}$$

where $\beta$ is the reciprocal of photoelectric-mixer efficiency.

In the investigated wavelength range, the high energy of individual photons necessitates taking into account the quantum nature of the carrier along with the noise.

According to the theorem of Kotel'nikov, the minimum signal capable of transmitting information is determined by the relationship $S_{min} = hf\Delta f$. As evident from (3) or (4), this signal level is lower than the level of the quantum noise.

From (3) or (4), depending on the structure of the receiver, it is possible to determine the range of communications in free space. Thus, for a heterodyne receiver:

$$R_{vac} = \left[\frac{PA}{\Omega \quad (N_{ex} + \beta hf\Delta f)\left(\frac{S}{N}\right)_0}\right]^{1/2}. \qquad (5)$$

As an example, let us calculate the communication range at a wavelength of 3.5 $\mu$ for $P = 1$ w, $A = 1$ m$^2$, $\Omega = 10^{-4}$, $(S/N)_0 = 5$, $\beta = 0.1$, and $\Delta f = 10^7$ cps. Because the external noise is very slight in the 3—5-$\mu$ range, let us consider that $\beta hf\Delta f \gg N_{ex}$. Then, according to (5), we have $R_{vac} = 1.8 \times 10^7$ km. This example shows that the communication range is quite considerable, especially since the power and solid angle of the transmitter beam are far from their limits.

In the presence of absorbing or scattering media, the communication range decreases considerably. In order to calculate the communication range in a medium with attenuation T per unit of length, let us write the following expression for light intensity at distance R from the source:

$$I = \frac{I_0}{R^2} T^R, \qquad (6)$$

where $I_0$ is light intensity at the beginning of the path. In the absence of attenuation, the same intensity would manifest itself at a longer distance $R_{vac}$ from the source:

$$I = \frac{I_0}{R^2_{vac}}. \qquad (7)$$

By equating (6) and (7), we obtain the relationship between attenuation, communication range in a vacuum, and communication range in the attenuating medium:

$$R^2 T^{-R} = R^2_{vac}. \qquad (8)$$

The attenuation of light in the atmosphere consists of its absorption by the gases which constitute the air envelope of the earth and in its scattering by particles contained in the air in the form of suspensions.

The spectrum of atmospheric absorption on a level with the earth's surface is shown in Fig. 2 [2], from which it follows that absorption

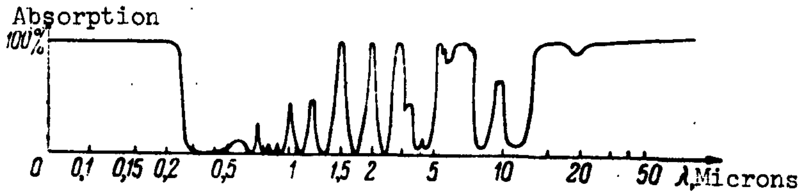


Fig. 2

is slight only in limited sectors — "windows" — in the visible and infrared regions of the spectrum. Ultraviolet and remote infrared radiation up to microwaves are almost completely absorbed by the atmosphere.

In order to compare the various windows of transparency from the standpoint of a maximum communication range, it is necessary to take into account the frequency dependence of the communication range in a vacuum and the attenuation of radiation at a given wavelength. As already stated, attenuation is caused not only by absorption, but also by scattering of light by particles suspended in the air, particularly by drops of water. The latter, depending on the weather, may occur in the form of haze, fog, or precipitation.

Light scattering depends both on light wavelength $\lambda$ and on particle radius $\rho$. At $\lambda \ll \rho$, scattering factor $k\rho$ does not depend on light wavelength and is proportional to $\rho^2$. At $\lambda > \rho$, the Rayleigh law according to which

$$\kappa_\rho = \frac{\rho^3}{\lambda^4}. \qquad (9)$$

is valid for scattering;

The distribution of drops of water according to size has been investigated by various methods. Experimental data have shown that the maximum of drop distribution in fog depends on altitude. On ascent above the earth's surface, the location of the maximum shifts toward larger drop radii. The discontinuity of the relief and the related vertical air flows, which increase the size of the drops, can have a marked influence on the distribution of drops according to size. The mean maximum size of drops varies from 1.5—2.5 μ for valleys and the

sea surface to 7—9 μ for highlands, where fogs have a transitional structure between valley fog and cloud [3].

On the basis of relationship (9), the scattering factor in the infrared region of the spectrum could be expected to be considerably lower than in the visible range. This represents a gain in range for communications in fog, because attenuation in the fog is primarily dictated by scattering.

In order to calculate the gain in communication range, it is necessary to make use of an analytical expression for the distribution of drops according to size. The formula for the asymptotic distribution of coagulating particles of Smolukhovskiy [4] is very close to the experimental distribution:

$$n(\rho)=\frac{25\,\rho^2 q}{4\pi\rho_m}\,e^{-\frac{5}{3}\frac{\rho^3}{\rho_m^3}}, \qquad (10)$$

where $\rho_m$ is the radius of particles corresponding to the maximum of distribution, and q is the water content of the fog.

Making use of this expression, we find the ratio of scattering factors for two wavelengths:

$$\frac{\epsilon_{\lambda_1}}{\epsilon_{\lambda_0}}=\frac{\Gamma\left(\frac{5}{3}\right)-\sum_{n=0}^{\infty}\frac{(-1)^n b_1^{\left(\frac{5}{3}+n\right)}}{n!\left(\frac{5}{3}+n\right)}+\frac{1}{a_1^4}\sum_{n=0}^{\infty}\frac{(-1)^n b_1^{(3+n)}}{n!\,(3+n)}}{\Gamma\left(\frac{5}{3}\right)-\sum_{n=0}^{\infty}\frac{(-1)^n b_0^{\left(\frac{5}{3}+n\right)}}{n!\left(\frac{5}{3}+n\right)}+\frac{1}{a_0^4}\sum_{n=0}^{\infty}\frac{(-1)^n b_0^{(3+n)}}{n!\,(3+n)}}, \qquad (11)$$

where $a_1$ and $a_0$ are the points of conjunction of Rayleigh and non-Rayleigh regions of scattering for wavelengths $\lambda_1$ and $\lambda_0$, $\Gamma(a)$ is the gamma function and $b = 5/3\,(a/\rho_m)^3$.

At $\lambda_0 \ll \rho_m$, relationship (11) takes the form:

$$\frac{\epsilon_{\lambda_1}}{\epsilon_{\lambda_0}}=1-\frac{\sum_{n=0}^{\infty}\frac{(-1)^n b_1^{\left(\frac{5}{3}+n\right)}}{n!\left(\frac{5}{3}+n\right)}+\frac{1}{a_1^4}\sum_{n=0}^{\infty}\frac{(-1)^n b_1^{(3+n)}}{n!\left(\frac{5}{3}+n\right)}}{\Gamma\left(\frac{5}{3}\right)}. \qquad (12)$$

Fig. 3 shows the dependence of $\varepsilon\lambda_1/\varepsilon\lambda_0$ on $\lambda/\rho_m$ calculated on the basis of relationship (12). It is seen that the light-scattering factor in fog drops sharply with an increase of $\lambda$ at $\lambda > \rho_m$. A decrease in $k\rho$ markedly increases the range of communication. Thus, the communication range in dense fog at a transmission coefficient of 0.003 and $\rho_m = 2\mu$ in the visible region of the spectrum would be—according to (8) — about 6 km, as against a communication range of $10^8$ km in a vacuum; at the same time, the scattering factor at a wavelength of 3.4 μ, from (12), would be about 250 times smaller, and the communication range in the atmosphere would increase to 120 km. A further increase in wavelength brings the communication range near the maximum determined by the transmission of the atmospheric window. On the basis of the foregoing, we have come to the conclusion that the selection of the operating wavelength is one of the essential factors affecting the range of optical communications in fog.

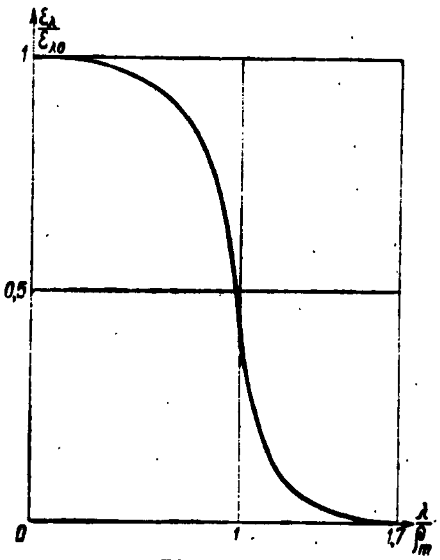

Fig. 3

The foregoing analysis is suitable for calculating the communication range between two objects on the earth's surface when the meteorological conditions are uniform along the entire path of communication. In some cases, for instance, for communications between Earth and space, the inhomogeneity of absorption and scattering along the path of communication must be taken into account. Likewise, it is necessary to take into account the difference in light scattering in clouds and fog caused by differing water-content spectra. The latter depend on altitude, temperature, and regime of the vertical air flow. According to numerous measurements made by various authors [5], the maximum of the water-content curve varies from 5—10 μ at the lower boundary of the cloud to 18—25 μ at an altitude of 1000 m above the cloud base. For calculations of scattering in clouds, (12) is inapplicable because at $\rho_m > 15\mu$ the gravitational mechanism of coagulation begins to play the main role, and in such cases distribution (10) represents but a rough approximation. For the larger drops, use can be made of the expression derived by A. Kh. Khrgian and I. P. Mazin [6]:

$$n(\rho)=\left(\frac{5}{2}\right)^5 \frac{q\rho^2}{\pi\rho_m^6}\, e^{-\frac{5\rho}{\rho_m}}, \qquad (13)$$

where q is the water content of the cloud.

Using this expression, we obtain

$$\frac{\varepsilon_{\lambda_1}}{\varepsilon_{\lambda_0}} = \frac{\sum_{\kappa=0}^{4} \frac{a_1^{\kappa}\ \rho_m^{6-\kappa}}{5^{4-\kappa}} C_4^{4-\kappa} + \frac{\rho^{\kappa}\, 8!}{a_1^4\, 5^{\kappa}} - \frac{1}{a_1^4} \sum_{\kappa=0}^{8} \frac{a_1^{\kappa}\ \rho_m^{8-\kappa}}{5^{8-\kappa}} C_8^{8-\kappa}}{\sum_{\kappa=0}^{4} \frac{a_0^{\kappa}\ \rho_m^{6-\kappa}}{5^{4-\kappa}} C_4^{4-\kappa} + \frac{\rho^{\kappa}\, 8!}{a_1^4\, 5^{\kappa}} - \frac{1}{a_0^4} \sum_{\kappa=0}^{8} \frac{a_0^{\kappa}\ \rho_m^{8-\kappa}}{5^{8-\kappa}} C_8^{8-\kappa}}, \tag{14}$$

where $C_m^n$ is the number of combinations of m by n.

At $\lambda_0 \ll \rho_m$, relationship (14) takes the form:

$$\frac{\varepsilon_{\lambda_1}}{\varepsilon_{\lambda_0}} = 1 - \frac{\sum_{\kappa=0}^{4} \frac{a_1^{\kappa} \rho_m^{4-\kappa}}{5^{4-\kappa}} C_4^{4-\kappa} - \frac{1}{a_1^4} \sum_{\kappa=0}^{8} \frac{a_1^{\kappa}\ \rho^{8-\kappa}}{5^{8-\kappa}} C_8^{8-\kappa}}{\frac{\rho_m^8\, 8!}{a_0^4\, 5^{\kappa}}}. \tag{15}$$

The fact that the values for $\rho_m$ in clouds are high makes it obvious from (15) that weak light scattering in the clouds and low light absorption in the atmosphere cannot occur simultaneously in any sector of the visible and infrared ranges of the spectrum. However, the comparatively small thickness of clouds gives reason to expect that it will be possible to establish optical communications through them. The communication range through a cloud or any other layer with a mean transmission $T_{\lambda\,av}$ and a thickness h is determined by the expression:

$$R^2_{ac} = (R-h)^2 h^2 T^{-k}_{\lambda\ av}. \tag{16}$$

For the sample optical frequency parameters given above, R from (16) would be approximately $10^5$ km for communication through a cumulus at Tav = 0.003 and an altitude of 2 km.

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